August 1982 LRP 212/82

OBSERVATION OF FAST CURRENT FLUCTUATIONS DURING INTERNAL DISRUPTIONS IN TCA, BY USING ALFVEN WAVE DIAGNOSTICS

A. de Chambrier, P.A. Duperrex, A. Heym,
F. Hofmann, B. Joye, R. Keller, A. Lietti,
J.B. Lister, A. Pochelon and W. Simm

OBSERVATION OF FAST CURRENT FLUCTUATIONS DURING INTERNAL DISRUPTIONS IN TCA, BY USING ALFVEN WAVE DIAGNOSTICS

A. de Chambrier, P.A. Duperrex, A. Heym, F. Hofmann, B. Joye,
R. Keller, A. Lietti, J.B. Lister, A. Pochelon and W. Simm

Centre de Recherches en Physique des Plasmas
Association Euratom - Confédération Suisse
Ecole Polytechnique Fédérale de Lausanne
21, Av. des Bains, CH-1007 Lausanne, Switzerland

ABSTRACT

Alfvén waves are excited in the TCA Tokamak by a fully toroidal antenna structure consisting of eight groups of 3 plates. When the plasma density is ramped during a discharge, the antenna loading shows several peaks of enhanced absorption corresponding to the excitation of Discrete Alfvén Waves. Internal disruptions produce a modulation of the resonance peaks at the sawtooth frequency which is attributed to q-profile fluctuations. The relative phase between the sawteeth seen on the soft X-ray flux and those on the resonance peaks gives information on the shape of the Alfvén frequency profile.

INTRODUCTION

The use of shear Alfvén waves as a diagnostic tool has recently been proposed by several authors [1-3]. The method is based on the experimental discovery [1,2] and theoretical interpretation [4] of Discrete Alfvén Waves (DAW) in Tokamaks. The resonance condition for these waves depends on the density profile and on the q-profile (in cylindrical approximation). Therefore, if one of these profiles is known, the DAW analysis allows one to draw conclusions about the other.

In this paper we apply the method to study fast current fluctuations during internal disruptions. In the past, temperature and density fluctuations have been analysed in detail in TFR [5]. However, no information has been obtained so far concerning the related current fluctuations. Alfvén wave diagnostics, on the other hand, give direct access to the q-profile, a parameter which is exceedingly difficult to measure in a Tokamak.

MEASUREMENTS

TCA is a Tokamak built with the aim of studying the excitation and absorption of Alfvén waves [1]. It has the following operating characteristics:

$R = 61$ cm

$a = 17$ cm

$B_\phi = 8\text{–}15$ kG

$I_p < 135$ kA

$2.2 < q(a) < 20$

$n_{eo} < 9 \cdot 10^{13}$ cm^{-3}

$T_{eo} = 700 - 1200$ eV

$T_{io} = 200 - 300$ eV

The waves are excited by an antenna structure inside the vacuum vessel. The complete structure consists of eight groups of three antenna plates, sited above and below the plasma at four equally-spaced toroidal locations. The phase of the current in each group can be inverted creating several possible excitation structures which can couple preferentially to different n, m modes.

Experiments described in this paper were performed at a fixed frequency (2.7 MHz) and the antennae were phased in such a way as to excite predominantly the $n = 2$, $m = \pm 1$ modes. When the plasma density is increased during a discharge we find several peaks of enhanced absorption. The peaks are seen both in the antenna loading (as deduced from the antenna voltage drop [7]) and in the rf magnetic field amplitude (measured by magnetic probes in the shadow of the limiter). Typical peaks are shown in the lower trace of fig. 1.

A close examination of the resonance peaks shows that they are modulated by MHD activity. This modulation is correlated with the sawtooth activity as seen in the soft X-ray signal (fig. 2). Two prominent patterns can be distinguished: On the leading edge of the peak labelled n = 2, the sawtooth modulation is in phase with the soft X-ray flux whereas on the peak labelled n = 4, the phase is inverted.

We claim that the sawtooth modulation of the resonance peaks is direct evidence for current profile fluctuations due to internal disruptions, as will be explained below.

THEORY

The shear Alfvén wave continuous spectrum, in the large aspect ratio approximation, is given by

$$\omega^2_{n,m} = \frac{B_\varphi^2}{\mu_0 \rho(r) R^2} \left[n + \frac{m}{q(r)} \right]^2 \qquad (1)$$

The function $\omega_{n,m}$ (Eq. 1) can be either monotonic (minimum at $r = 0$) or nonmonotonic (minimum at $r = r_{min}$) depending on the density and current profiles. If we assume profiles of the form

$$j = j_0 \left(1 - \frac{r^2}{a^2}\right)^{K_j} \qquad \rho = \rho_0 \left(1 - \frac{r^2}{a^2}\right)^{K_\rho}$$

the frequency profile is monotonic when the inequality

$$\frac{n\,q(0)}{m} \geqslant \frac{K_j}{K_\rho} - 1 \qquad (2)$$

holds and nonmonotonic otherwise.

The discrete Alfvén waves, which are responsible for the peaks observed in the experiment, have their resonance frequencies just below the lower edge of the Alfvén continua [2,3,4] as given by (1). The frequency difference between the lower edge of a continuum and the corresponding DAW depends on the mode numbers but is generally small [2,4]. When the density increases, as is the case in the experiment, $\omega_{n,m}(o)$ decreases until its minimum comes close to the antenna frequency ω_{ant} and a DAW is excited. The crucial question is what happens to the DAW resonance when the density and current profiles fluctuate, due to internal disruptions?

Fluctuations in density or current profiles obviously produce fluctuations in the frequency profile as given by eq. (1). Temperature and density fluctuations have been analysed in detail on TFR [5]. It has been shown that the temperature and density fluctuation is zero at a certain radius $r = r_{inv}$ and that the phase is inverted on either side of $r = r_{inv}$. The inversion radius r_{inv} has been shown to be close to the $q = 1$ surface [8,9]. It follows that the frequency profile (1) will also have a zero fluctuation amplitude at $r = r_{inv}$ and a phase inversion at that point. The minimum of the frequency profile oscillates with a given phase when $r_{min} < r_{inv}$ and with opposite phase when $r_{inv} > r_{min}$. Since the DAW-frequency is tied to the minimum, it will behave the same way.

The passage through a DAW resonance can be described by a function of the form

$$b = A_o \left[(\omega_{ant} - \omega_{DA,min})^2 + \Gamma^2 \right]^{-1} \quad (3)$$

where b is the wave field amplitude, Γ is the width of the peak and A_o is a constant. We have computed the function (3) making the following assumptions:

The inversion radius of the current and density profiles is assumed to be $r_{inv} \cong 0.55\ a/\sqrt{q(a)}$, deduced from soft X-ray measurements [8,9]. The unperturbed central q-value is fixed at q(o) = 0.95. We further assume that the current follows the T_e fluctuations, with $j \sim T_e^{3/2}$, even though the time scale of internal disruptions is much faster than the resistive time scale. In computing the function (3) we use measured values for the electron temperature fluctuations, the peak width Γ, the mode numbers n,m and the safety factor q(a). The value of $\Delta T_e/T_e$ is obtained from the soft X-ray flux, assuming $\phi_x \sim n_e T_e^{\alpha(T_e)}$ where $\alpha(T_e)$ is a known function characterizing the instrument. T_{eo} is measured by soft X-rays and Thomson scattering.

The quantities κ_ρ and $\Delta n_e/n_e$ are considered as free parameters. They are adjusted in order to get the best agreement between simulation and experiment. κ_j is given by $\kappa_j = q(a)/q(o) - 1$. The result is shown in fig. 3. The values for κ_ρ and $\Delta n_e/n_e$ which were otained from the fitting are consistent with measurements on other Tokamaks.

DISCUSSION

The relative importance of density and temperature fluctuations can be estimated by differentiating (1), assuming $1/q(o) \sim j(o) \sim T_{eo}^{3/2}$:

$$\frac{\Delta\omega_{DAW}}{\omega_{DAW}} = -\frac{1}{2}\frac{\Delta n_e}{n_e} + \frac{3}{2}\frac{\Delta T_e}{T_e}\left[\frac{m}{nq+m}\right] \qquad (4)$$

We note that, for $n = 2$, $m = 1$, $\Delta\omega_{DAW}$ vanishes when $\Delta n_e/n_e \approx \Delta T_e/T_e$. It is known, however, that the density fluctuations due to internal disruptions are about one order of magnitude smaller than the temperature fluctuations. We conclude that, for the low-n modes considered here, the effect of density fluctuations is generally small compared with temperature and current fluctuations. $\Delta\omega_{DAW}$ can be positive or negative depending on whether Δq is sampled inside or outside the inversion radius.

From the comparision between experimental (fig. 2) and computed curves (Fig. 3), we draw the conclusion that the $n = 4$ peak corresponds to a monotonic frequency profile, whereas the $n = 2$ peak shows evidence for a nonmonotonic profile. Going back to (2), we note that a transition between monotonic and nonmonotonic at $n = 3$ implies $\kappa_j/\kappa_p \approx 4$, a value which is consistent with commonly measured profiles.

The theoretical interpretation of our measurements, as given in the previous section, obviously hinges on the identification of the modes. A parameter scan in the n_e vs. $1/q(a)$ plane [2] has shown that the DAW resonance can only be seen on those modes, the wave vectors of which have the same helicity as the static magnetic field. This corresponds to m = +1 in our terminology. The toroidal mode number, n, is obtained by applying (1). A second method for identifying the modes relies on magnetic probe measurements in the shadow of the limiter: in the large aspect ratio approximation, the components of the rf field, in vacuum, satisfy the relation

$$\frac{m}{n} = \frac{r b_\theta}{R b_\varphi} \tag{5}$$

Further information concerning the identification of modes can be obtained by varying the phasing of the antenna currents [2].

Apart from the sawtooth modulation, we have also observed fluctuations on the resonance peaks at higher frequency (~ 10 kHz) presumably caused by magnetic island activity. In fact, a variation in the current profile caused by the rotation of an island, located on the q = 1 surface, can also produce a modulation of the resonance frequency. The 10 kHz modulation is usually observed to be strongest at the n = 3 peak. This supports our hypothesis that the Alfvén frequency profile undergoes a transition between monotonic and nonmonotonic at n = 3, because if this hypothesis is true, the n = 3 mode has the flattest frequency profile near the axis and this mode should be extremely sensitive to variations in the current and density distribution in the vicinity of the q = 1 surface. In Fig. 1 we note that the 10 kHz oscillation of the b_θ amplitude is indeed larger on the n = 3 peak than it is on the n = 2 peak. On the other hand, the prominent Mirnov activity that is seen in the upper trace of fig. 1, between the n = 2 and n = 3 peaks, does not appear in the rf wavefield (lower trace). This indicates that our measurement is not sensitive to island activity at the edge of the plasma. Finally, it should be mentioned that the sawtooth oscillations in the b_θ amplitude are exactly in phase (or in opposite phase) with the oscillation in the soft X-ray flux originating from the centre of the plasma. This confirms our theoretical interpretation, as given in the previous section, which implies that the rf wavefield measured in the shadow of the limiter gives us information on what is happening in the core of the plasma.

In conclusion, we have shown that the DAW can be used to measure fast variations in the q profile in a Tokamak discharge, and, in particular, that internal disruptions produce fast relaxations of the current profile.

Discussions with K. Appert, R. Gruber, F. Troyon and J. Vaclavik are gratefully acknowledged. This work was partially supported by the Swiss National Science Foundation.

REFERENCES

[1] A. de Chambrier et al., accepted for publication in Plasma Physics 24 (1982).

[2] A. de Chambrier et al., 3rd Joint Varennea-Grenoble Symposium on Heating in Toroidal Plasmas, Grenoble 1982, Vol. 1, 161.

[3] D.W. Ross, G.L. Chen and S.M. Mahajan, Phys. Fluids 25 (1982) 652 and D.W. Ross et al., Austin Report FRCR 223 (1981).

[4] K. Appert, R. Gruber, F. Troyon and J. Vaclavik, accepted for publication in Plasma Physics 24 (1982).

[5] TFR Group, Plasma Physics 19 (1977), 349.

[6] Cheetham A.D. et al., 11th Symposium on Fusion Technology, Oxford, Vol. 1 (1980), 601.

[7] A. Lietti et al., 9th Symposium on Eng. Probl. of Fus. Res., Chicago (1981), 835.

[8] M. Dubois, D. Marty and A. Pochelon, Nucl. Fusion 20, (1980), 1355.

[9] Equipe TFR, IAEA Berchtesgaden (1976), Vol. 1, Vienne (1977), 279.

FIGURE CAPTIONS

Fig. 1: $n = 2$ and $n = 3$ DAW peaks during a 100 ms discharge

Upper trace: Mirnov activity $\tilde{B}_\theta$

Lower trace: RF wave-field $|b_\theta|$

Fig. 2: Modulation of the wave-field by sawtooth activity

a) $n = 2$ b) $n = 4$

Fig. 3: Simulation of the DAW peak modulation

a) $n = 2$ b) $n = 4$

The minimum radius of the corresponding Alfvén frequency profile is also shown. Quantities carrying an asterisk have been obtained by optimizing the fit to the measured patterns.

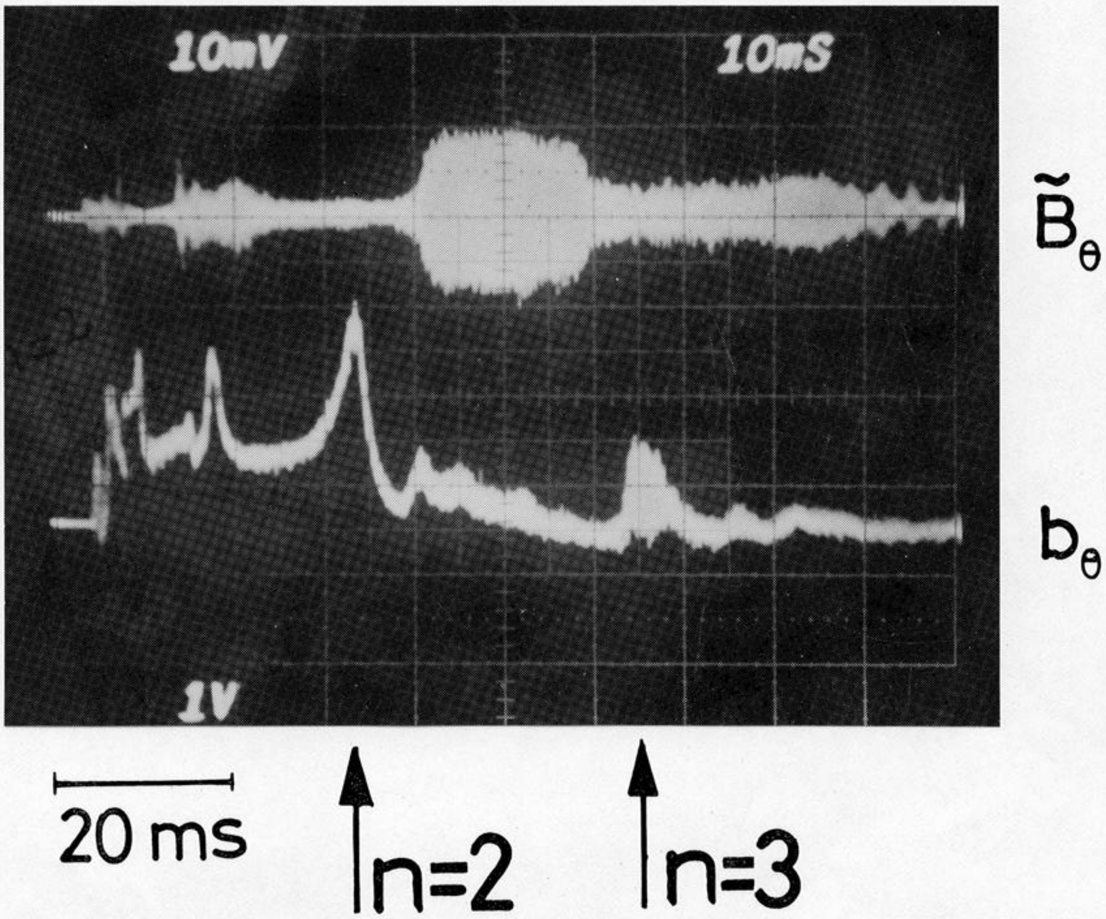


Fig. 1

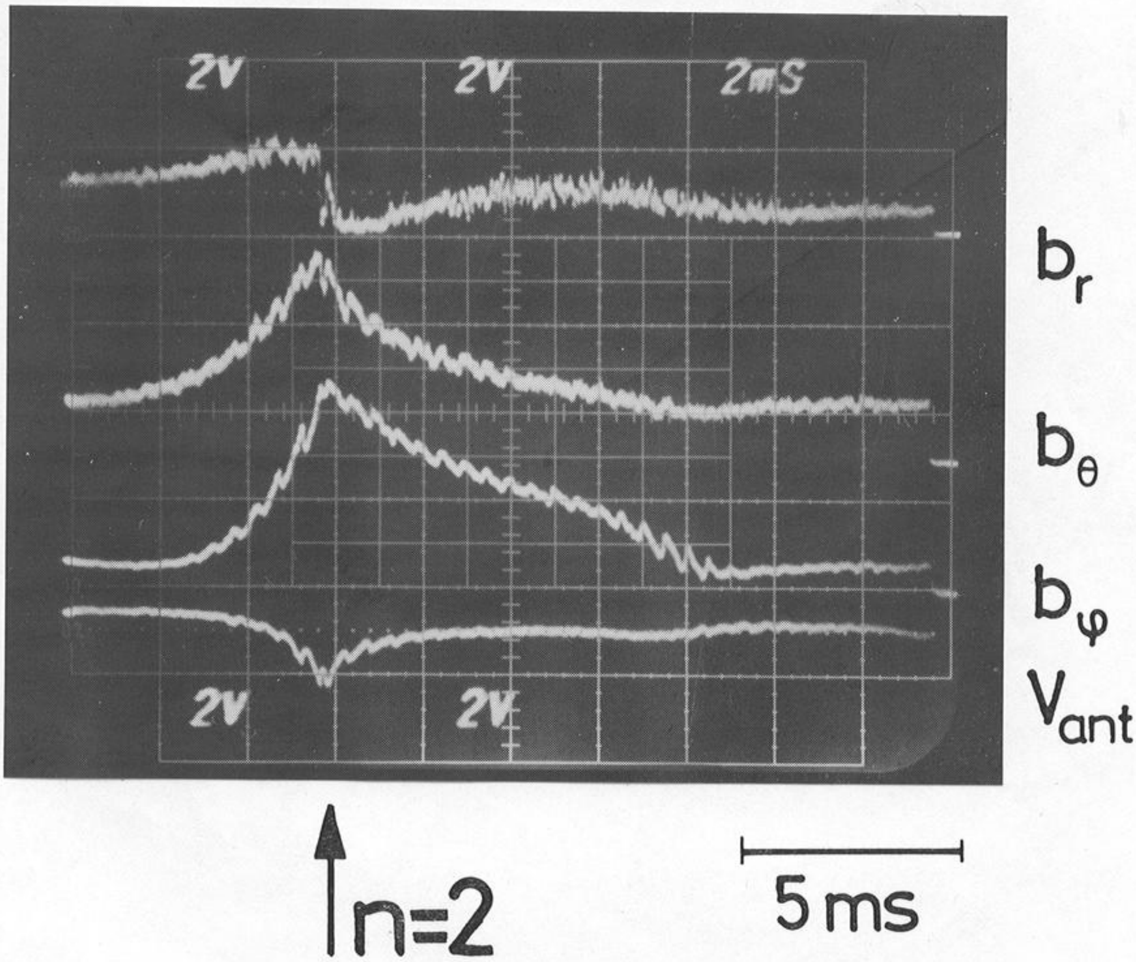


Fig. 2a

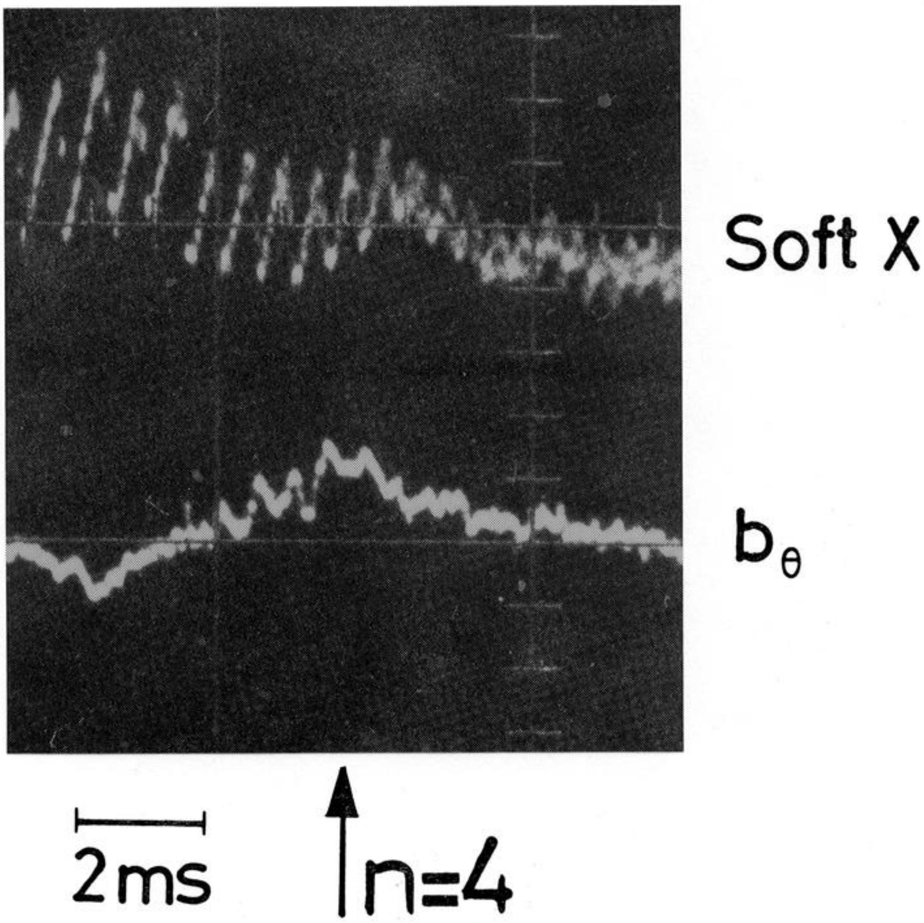
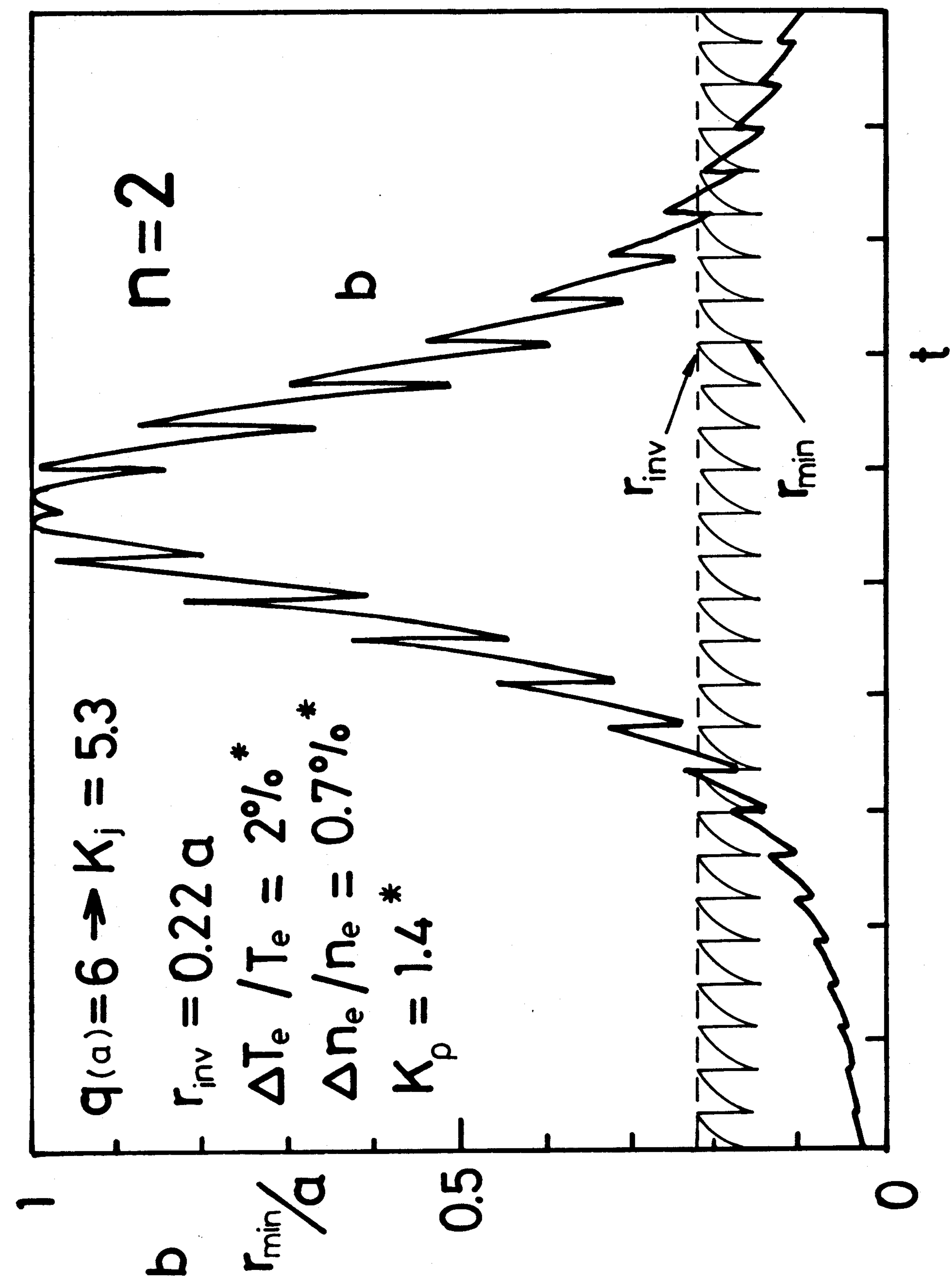
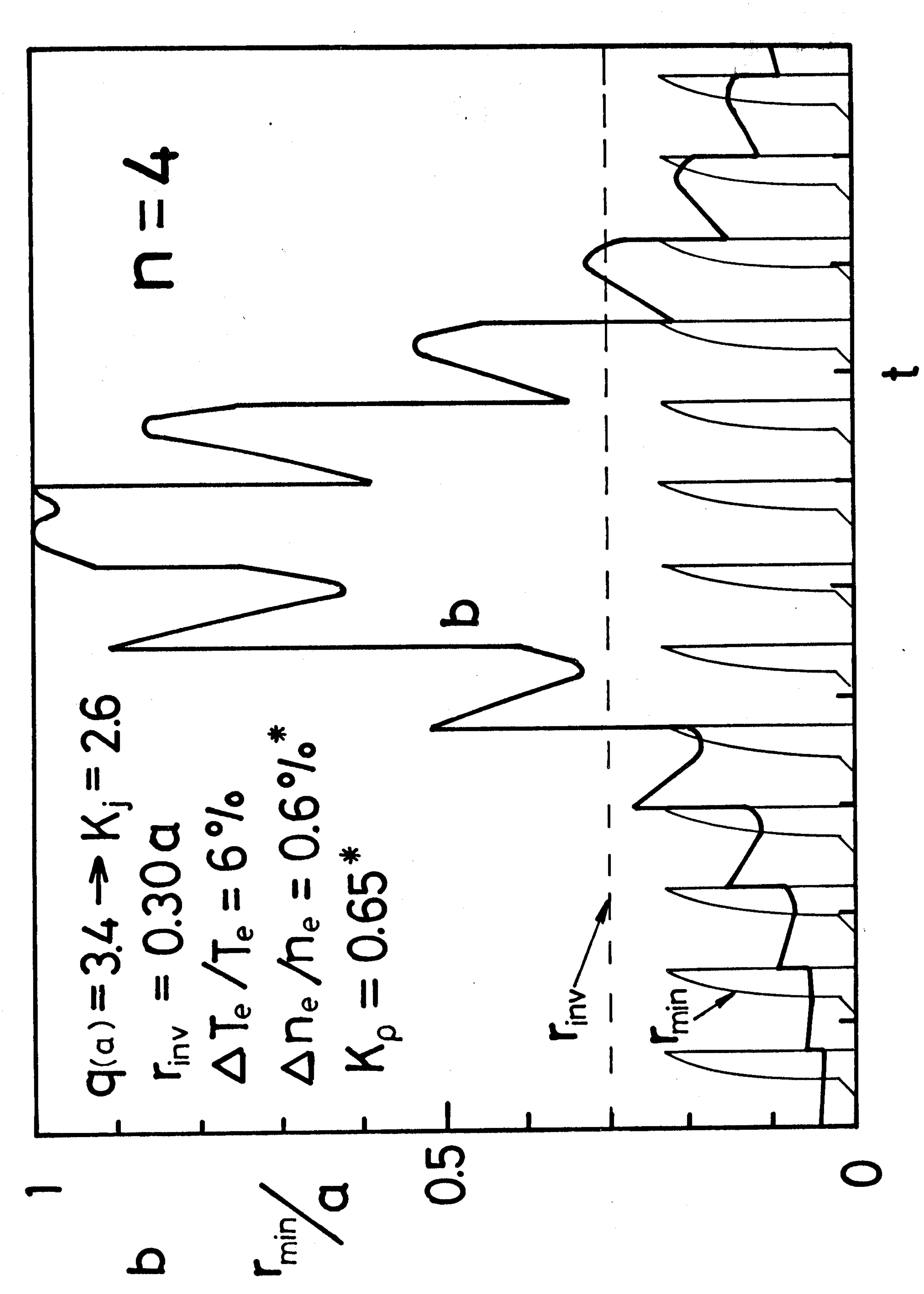


Fig. 2b



q(a) = 6 → K_j = 5.3
r_{inv} = 0.22 a
$\Delta T_e / T_e$ = 2%*
$\Delta n_e / n_e$ = 0.7%*
K_ρ = 1.4*
n=2
b
b
r_{min}/a
1
0.5
0
t
r_{inv}
r_{min}

Fig. 3a



b
r_{min}/a
1
0.5
0
t
n = 4
$q(a) = 3.4 \rightarrow K_j = 2.6$
$r_{inv} = 0.30a$
$\Delta T_e / T_e = 6\%$
$\Delta n_e / n_e = 0.6\%^*$
$K_\rho = 0.65^*$
b
r_{inv}
r_{min}

Fig. 3b